Docket No. - BAT 0064 PA/40078.252

AMPLIFYING WAVELENGTH DIVISION MUX/DEMUX

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Serial No. 60/425,939, filed November 13, 2002.

BACKGROUND OF THE INVENTION

The present invention relates generally to the propagation, direction, conditioning and other control of optical signals in optical devices and, more particularly, to the control of optical signals consisting of multiple spectral components. Modern telecommunications networks, for example, utilize a variety of optical components to affect control of multi-component optical signals. The present invention presents a scheme for addressing design and performance considerations related to handling multi-component optical signals of such networks.

For the purposes of defining and describing the present invention, it is noted that the use of the term "optical" throughout the present description and claims is not intended to define a limit to any particular wavelength or portion of the electromagnetic spectrum. Rather, the term "optical" is defined herein to cover any wavelength of electromagnetic radiation capable of propagating in a suitable signal propagating structure. For example, optical signals in the infrared regions of 850, 1350, 1400 and 1550 nm are commonly used in optical telecommunications.

BRIEF SUMMARY OF THE INVENTION

The present inventors have recognized a need for an improved scheme for the control of optical signals in optical devices and, more particularly, for improved control of multi-component optical signals. This need is met by the present invention.

In accordance with one embodiment of the present invention, an integrated optical device is provided comprising a waveguide body, a spectral combiner/divider, a primary input/output channel, and a set of displaced input/output channels. The waveguide body is configured to permit propagation of an optical signal having multiple spectral components. At least a substantial portion of the waveguide body comprises an optical amplification medium configured

to amplify different spectral components of the multi-component optical signal. The spectral combiner/divider is near a boundary of the waveguide body and is configured such that (i) a spatial distribution of an optical signal propagating to and from the spectral combiner/divider is a function of respective component wavelengths of the multi-component optical signal, and (ii) a substantial portion of the optical signal propagates through the optical amplification medium. The primary input/output channel and the set of displaced input/output channels are defined in the waveguide body. The displacement of each of the displaced input/output channels from the primary input/output channel is defined at least in part by the spectral combiner/divider. A substantial portion of the optical signal in the primary input/output channel, the set of displaced input/output channels, or both, propagates through the optical amplification medium.

In accordance with another embodiment of the present invention, an integrated optical device is provided where the primary input/output channel defines a multidirectional path propagating through the optical amplification medium.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided where the primary input/output channel defines a configuration designed to yield optical signal amplification sufficient to offset optical losses in the integrated optical device.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising an erbium or ytterbium-doped glass slab waveguide body and a spectral combiner/divider. The waveguide body is configured to permit propagation of an optical signal having multiple spectral components. The waveguide body is doped with sufficient erbium or ytterbium for amplification of different spectral components of the multi-component optical signal. The spectral combiner/divider is at a curved periphery of the waveguide body. The curved periphery and the spectral combiner/divider are configured such that the multi-component optical signal propagates from an input/output face of the waveguide body, through the waveguide body to the spectral combiner/divider at the curved periphery of the waveguide body, back through the waveguide body, as reflected by the spectral combiner/divider, and to the input/output face of the waveguide body. A spatially condensed optical signal propagating from the input/output face of the waveguide body to the spectral combiner/divider, and from the spectral combiner/divider to the input/output face, is spatially

expanded by the spectral combiner/divider according to respective component wavelengths of the multi-component optical signal. A spatially expanded optical signal propagating from an input/output face of the waveguide body to the spectral combiner/divider, and from the spectral combiner/divider to the input/output face, is spatially condensed by the spectral combiner/divider according to respective component wavelengths of the multi-component optical signal. The spatially condensed optical signal propagating between the input/output face of the waveguide body and the spectral combiner/divider defines a primary input/output channel in the waveguide body. The spatially expanded optical signal propagating between the input/output face of the waveguide body and the spectral combiner/divider defines a set of displaced input/output channels in the waveguide body. The displacement of each of the displaced input/output channels from the primary input/output channel along the input/output face is defined by the spectral combiner/divider.

In accordance with yet another embodiment of the present invention, a telecommunications or other type of optical network is provided comprising at least one transmitter, at least one regenerator, and at least one receiver. The transmitter is configured to transmit an optical signal having multiple spectral components. The regenerator is configured to amplify the multi-component optical signal. The receiver is configured to receive the multi-component optical signal. The transmitter, regenerator, receiver, or combinations thereof, comprise one or more integrated optical devices according to the present invention.

Accordingly, it is an object of the present invention to provide for improved propagation, direction, conditioning and other control of optical signals in optical devices and optical networks. Other objects of the present invention will be apparent in light of the description of the invention embodied herein.

In accordance with yet another embodiment of the invention, an optical sensor is provided which uses the evanescent tail of the waveguiding region to sense the attachment of particles or materials on the surface of the waveguide in a multi-channel format.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The following detailed description of specific embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

Fig. 1 is a schematic illustration of an integrated optical device in accordance with one embodiment of the present invention;

Figs. 2-5 are schematic illustrations of integrated optical devices in accordance with alternative embodiments of the present invention;

Fig. 6 is a schematic illustration of an integrated optical device in accordance with a further alternative embodiment of the present invention; and

Fig. 7 is a schematic illustration of an optical network.

DETAILED DESCRIPTION

Referring initially to Fig. 1, an integrated optical device **10** according to one embodiment of the present invention is illustrated schematically. The integrated optical device **10** comprises a waveguide body **20**, a spectral combiner/divider **30**, a primary input/output channel **40**, and a set of displaced input/output channels **50**.

The waveguide body **20** is constructed of a material suitable for permitting propagation of an optical signal there through. For example, the waveguide body **20** may comprise silica or another glass, a polymeric material, or any other material suitable for propagation of optical signals having a plurality of different spectral components. Further, the waveguide body is configured to amplify different spectral components of the multi-component optical signal. For example, the waveguide body **20**, or at least a substantial portion of it, may be doped with an optical amplification medium **22**. Although the illustrated embodiment shows a waveguide body **20** where substantially all of the waveguide body **20** comprises the optical amplification medium **22**, it is contemplated that suitable selective presentation of the optical amplification medium **22** would allow for provision of the optical amplification medium **22** in a lesser portion or a mere majority of the waveguide body **20**.

The optical amplification medium receives light energy from an external source, e.g., a laser diode that pumps light into a fiber, and acts as a laser in its own right. The external light energy raises the energy level of atoms in the optical amplification medium **22**, creating a population inversion of states. The population inversion of states is necessary for stimulated emission to occur. The emission stimulated in the optical amplification medium is coherent with and therefore amplifies the optical signal propagating through the waveguide body **20**. In this manner, the optical signal propagates through the optical amplification medium **22** and may be subject to amplification by using, for example, a pump laser. Suitable dopants include erbium, neodymium, ytterbium, praseodymium, samarium, terbium, and other rare earth elements, transition metals, or other optically active elements. It is contemplated that the waveguide body may include other additives or dopants in addition to the optical amplification medium.

The spectral combiner/divider **30** is positioned near a boundary **24** of the waveguide body **20** and is configured to aid in multiplexing or demultiplexing the spectral components of an optical signal. The spatial distribution of an optical signal propagating to and from the spectral

combiner/divider **30** is a function of the respective component wavelengths of the multi-component optical signal. More specifically, a spatially condensed, multiplexed multi-component optical signal propagating from an input/output face **25** of the waveguide body **20** to the spectral combiner/divider **30** is spatially expanded by the spectral combiner/divider **30** according to the respective component wavelengths of the multi-component optical signal. The signal is then directed back to the input/output face **25** as a spatially expanded, demultiplexed optical signal. Similarly, a spatially expanded, demultiplexed optical signal propagating from the input/output face **25** to the spectral combiner/divider **30** is spatially condensed by the spectral combiner/divider **30** according to respective component wavelengths of the multi-component optical signal. The signal is then directed back to the input/output face **25** as a spatially condensed, multiplexed optical signal.

The spectral combiner/divider **30** may take the form of a reflective grating structure (e.g., a reflective diffraction grating), as is illustrated in Figs. 1-6. However, it is noted that any one or more of a plurality of suitable alternative structures may be employed to achieve spectral combination or division according to the present invention. For example, it is contemplated that an echelle grating, a holographically-formed reflective grating, a Rowland circle grating, a reflector stack, a wavelength selective interference filter, a flat specular reflection surface, a side-tap waveguide grating, a Bragg grating, and a super-dispersive prism formed by a photonic bandgap structure would all have utility in defining the spectral combiner/divider **30** of the present invention.

A primary input/output channel **26** and a set of displaced input/output channels **28** are defined in the waveguide body **20**. Each of the displaced input/output channels **28** are displaced from the primary input/output channel **26** by a distance and direction that is defined, at least in part, by the optical characteristics of the spectral combiner/divider **30**. For example, referring to the illustrated embodiments, where an optical signal to be demultiplexed is input through the input/output channel **26**, the spectral combiner/divider **30** spatially distributes the signal based upon wavelength differences of components in the signal. The displaced input/output channels **28** are positioned to receive individual ones of the spatially distributed signals.

The primary input output channel **26**, the spectral combiner/divider **30**, and the set of displaced input/output channels **28** define a folded optical path along which the optical signal

propagates. In the illustrated embodiment, the waveguide body **20**, the spectral combiner/divider **30**, and the optical amplification medium are configured such that substantially the entire optical signal propagating to the spectral combiner/divider **30** and substantially the entire optical signal propagating from the spectral combiner/divider **30** propagate through the optical amplification medium **22**. At least a portion of the optical signal propagating to and from the spectral combiner/divider **30** should propagate through the optical amplification medium **22**. In Figs. **1-3**, the optical amplification medium is present along both legs of the folded optical path. In the embodiment of Fig. 6, the optical amplification medium is present along all legs of the folded optical path. Of course, it is contemplated that the optical amplification medium **22** may be present along only one leg, or less than all legs, of the folded optical path.

In the embodiment illustrated in Figs. 1 and 4-6, the spectral combiner/divider **30** is formed at an interface with the boundary **24** of the waveguide body **20** by securing it to the boundary **24** of the waveguide body **20**. It may be preferable to provide for some type of optical coupling between the spectral combiner/divider **30** and the waveguide body **20**. As is illustrated in Fig. **3**, it is noted that the spectral combiner/divider **30** may be formed in the waveguide body **20** at the periphery of the body **20** or inland of the periphery. Similarly, as is illustrated in Fig. 2, the spectral combiner/divider **30** may be formed integral with the waveguide body **20**, as an extension of the waveguide body **20**.

Comparing Figs. 1 and 2, it is noted that the primary input/output channel **26** and the set of displaced input/output channels **28** may be defined in the waveguide body **20** by input/output structure formed within the waveguide body or at an interface with the waveguide body **20**. More specifically, in the embodiment of Fig. 1, the primary input/output channel **26** and the set of displaced input/output channels **28** are defined in the waveguide body **20** by suitable ridge or buried waveguides or other optical signal propagating structure. In contrast, referring to Fig. **2** the primary input/output channel **26** and the set of displaced input/output channels **28** are merely defined in the waveguide body **20** by suitable optical signal propagating structure (not shown) that is optically coupled to or formed at an interface with the waveguide body **20**. To clarify, it is noted that a primary or displaced input/output channel may be "defined in" the waveguide body by providing input/output structure within the waveguide body, at an interface with the waveguide body, or coupled to the waveguide body.

Turning to Figs. 4 and 5, the primary input/output channel **26** may be presented as a multi-directional spiral waveguide **35** to maximize potential signal amplification and enhance the versatility of the integrated optical device **10** of the present invention. The spiral waveguide **35** may be configured to avoid crossing itself, as is illustrated in Fig. 4, or may be a folded spiral waveguide **35** that crosses itself at one or more points along the waveguide **35**, as is illustrated in Fig. 5. The resulting increase in waveguide length allows for increased amplification using external light energy from a pump source 45 in the form of, for example, a pump laser. The structure of the spiral waveguide and the manner in which it is formed is beyond the scope of the present invention but may be gleaned from conventional and yet to be developed teachings on the subject of planar waveguides.

The spiral waveguides **35** of Figs. 4 and 5 are well suited for tailoring the amplification of the optical signal to offset for optical losses of the integrated optical device **10** because the length of the optical path defined by the spiral waveguide **35** can be tailored to achieve optimum amplification. The level of amplification may be set to any desired value including a desired net gain value for the device. However, according to one embodiment of the present invention, the level of amplification is set to a value selected to offset optical losses, including but not limited to absorptive and insertion losses, throughout the optical device **10**. For example, the energy density of the light from the external light source used for pumping the optical amplification medium **22** may be significantly reduced in specific low pump density areas 47 of the device **10**. In these areas of relatively low pump density, the pump energy density may be too low to overcome the absorption losses attributable to the amplification medium, in which case the population inversion of states necessary for stimulated emission will not occur and absorptive optical losses will result. The effect of these optical losses can be offset by ensuring that the spiral waveguide **35** is positioned in relatively high pump density areas **49** and defines an optical path length in those areas that is sufficient to offset the losses in the relatively low pump density areas. Although the low and high pump density areas **47, 49** are delineated in Figs. 4 and 5 with a clear demarcation between the two areas, the actual transition from one region to the next will be less definitely defined and may occur at a variety of locations in the device 10 depending partly upon the nature of the pump source.

The spiral waveguides illustrated in Figs. 4 and 5 are referred to herein as "multi-directional" waveguides because the waveguide itself travels in at least two different directions to increase its path length in relatively high pump density areas **49**. It is contemplated that any suitable multi-directional waveguide configuration may be utilized in place of the spiral waveguides **35** of Figs. 4 and 5 to increase the available optical path length in the areas **49** of relatively high pump density.

Use of the spiral waveguide **35** also allows for the reduction of the dopant level of the optical amplification medium **22**. Specifically, the dopant level of the entire optical device **10** may be reduced because the optical device **10** can be configured such that the spiral waveguide **35** defines an extended path length in areas of high pump density. Areas of relatively low pump density thus contribute less absorptive loss to the device as a whole because of the reduced dopant level. It is contemplated that an optimum dopant level and spiral waveguide configuration may be achieved to offset the overall absorptive loss of the optical device **10** or, more specifically, to balance the absorptive loss and the optical signal amplification of the device **10**.

A variety of factors affect the degree to which the optical signal amplification offset the optical losses, including, but not limited to: (i) the optical configuration of the primary input/output channel, including characteristics such as its optical path length, geometry, and position within the high pump density areas; (ii) the choice of amplification medium dopant and dopant level; (iii) the length of the optical path in the low pump density area; and (iv) the overall device layout and configuration; and (iv) the curvature or focal length of the device. Any one or more of these factors can be utilized and controlled to achieve the gain/loss offset and balance described herein.

Returning briefly to the embodiments of Figs. 1-3, where a substantially linear primary input/output channel **26** is utilized, it is contemplated that the dopant level in the device **10** and the length and position of the primary input/output channel **26** may also be optimized to achieve a desired gain or to offset or balance the overall optical loss of the optical device **10**.

Referring to Fig. 6, an alternative integrated optical device **10** according to the present invention is illustrated. The device **10** includes a partially transmissive reflector **40** positioned along the folded optical path defined by the primary input output channel **26**, the spectral

combiner/divider **30**, and the set of displaced input/output channels **28**. An additional reflector **50** is provided at a curved periphery of the waveguide body **20** to enable redirection of an optical signal reflected by the partially transmissive reflector **40**. In this manner, first, second, and third folds are defined in the optical path and the optical signal is directed along an optical path that begins and ends at the input/output face **25** of the waveguide body **20**.

A detector **42** may be positioned along the optical path to detect that portion of the optical signal transmitted through the partially transmissive reflector **40**. In this manner, the partially transmissive reflector **40** and the detector **42** function as an optical signal monitor in the folded optical path. It is contemplated that alternative structure may be provided to yield a suitable optical signal monitor.

It is further contemplated that block element **40** may alternatively comprise an optical signal filter **40** in the form of a wavelength selective reflector or another type of suitable filter. In this manner, the integrated optical device may be employed to permit transmission or reflection of only selected wavelength portions of the optical signal. It is noted that an optical signal filter may be positioned at any one of a number of suitable positions along the folded optical path. It is further noted that an optical signal filter **40** may be employed with the detector **42** as a filtered optical signal monitor to detect portions of the optical signal in one or more specific wavelength bands.

Referring to Fig. 7, we note that integrated optical devices of the present invention may be employed in a telecommunications or other type of optical network **50**. Optical networks **50** typically comprise, among other things, transmitters **60**, regenerators **70**, and receivers **80**. The optical transmitter **60** is configured to transmit an optical signal having multiple spectral components. The regenerator **70** is used to amplify the multi-component optical signal generated by the transmitter **60**. The receiver **80** is configured to receive the multi-component optical signal generated by the transmitter and amplified by the regenerator. A given optical network **50** will typically employ a plurality of transmitters **60**, regenerators **70**, and receivers **80** and each of these components may control the optical signal in a variety of ways. Integrated optical devices according to the present invention will have utility in such components where the functionality of the component allows for, or requires, amplification of the optical signal as its spectral components are spatially expanded or condensed.

Typically, in telecommunications and other types of optical networks, an optical transmitter **60** will require multiplexing or spatial condensing of the spectral components of an optical signal while an optical receiver **80** will require demultiplexing or spatial expansion of an optical signal. Accordingly, it is contemplated that use of a multiplexing integrated optical device according to the present invention would be advantageous in the context of an optical transmitter **60** of an optical network. Similarly, it is contemplated that use of a demultiplexing integrated optical device according to the present invention, which can reduce the optical signal losses incurred by typical demultiplexers, would be advantageous in the context of an optical receiver **80**. It is further contemplated that use of an integrated optical device according to the present invention may also be advantageous in the context of an optical regenerator **70**. More specifically, where the transmitter **60** comprises an integrated optical device according to the present invention, the primary input/output channel **26** of the optical device is coupled to an input channel of the regenerator **70** or the receiver **80**. Where the receiver **80** comprises an integrated optical device according to the present invention, the primary input/output channel **26** of the device is coupled to an output channel of the regenerator **70** or the transmitter.

It is further contemplated that an integrated optical device according to the present invention may be employed as an optical sensor by utilizing the evanescent tail of the waveguiding region of the waveguide body 20 to sense the attachment of particles or materials on the surface of the waveguide body 20. Specifically, particles or materials present on the surface of the waveguiding region will lead to attenuation of the evanescent field. This attenuation can be detected at the output of the device as changes in the output spectrum or otherwise. The nature of the attenuation will be indicative of the presence of certain particles or materials, i.e., chemical materials, biological material, inorganic or organic materials, etc. The set of displaced input/output channels 28 of the waveguide body 20 can effectively provide particle or material sensing in a multi-channel format.

It is noted that terms like "preferably," "commonly," and "typically" are not utilized herein to limit the scope of the claimed invention or to imply that certain features are critical, essential, or even important to the structure or function of the claimed invention. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the present invention.

For the purposes of describing and defining the present invention it is noted that the term "substantially" is utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. The term "substantially" is also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

Having described the invention in detail and by reference to specific embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims. More specifically, although some aspects of the present invention are identified herein as preferred or particularly advantageous, it is contemplated that the present invention is not necessarily limited to these preferred aspects of the invention.

What is claimed is: